Investigation into rheological properties of compacted loess soils

L'étude de propriétés rhéologiques des sols loessiques compactés

S.K.Aliyev & A.I.Veliyev – *Azerbaijan Architecture and Building University, Baku*

ABSTRACT: The paper presents the pesults of laboratory experimental investigations into creep deformation and long-term strength of compacted loess soils. A rheological equation of state is obtained, i. e. relationship among deformation, stress and time is revealed. An equation of long-term strength of compacted loess soils is obtained. Values of parameters of equations of the rheological state and long-term strength for different states of density of loess soils are determined. At the parameters known from experiments the obtained equation allow to predict the performance of compacted loess soil in structures foundations with time.

RÉSUMÉ: Le rapport donne les résullats de recherches experimentelles de laboratoire en déformation de fluoge et la resistance de longue durée des sols loessiques compactés. Une équation rhéologique d'état est obtenue – done, un lien entre la déformation, la contrainte et le temps est découvri. Une équation de la résistance de longue durée des sols loessiques compactés est obtenue. Les valeurs de parametres des équations de létat rhéologique et de la résistance de longue durée pour les états diverses de la densité du sol loessique sont determineés. Avec les paramétres connues parles épreuves les équations obtenues permettent de prédire le comportement du sol loessique compacté dans des fondations de bàtiments avec le temps.

Various engineering methods excluding adverse consequences of subsidence are known to be used in erecting engineering structures. One of these methods is compaction of subsiding soils by different ways. Lesser water permeability and greater bearing capacity are typical of compacted loess soils.

The construction practice, however, demonstrates that the compacted loess soils in structures foundations have rheological properties due to which the structures get long-term and larger undesirable deformations. For this reason the possibility of appearance of such deformations during the use of engineering structures must be eliminated through consideration for rheological properties of soil foundations in the process of design.

The consideration for rheological properties of the compacted loess soils in the structures' foundations requires determination of regularities of creep and long-term strength at their different state of density.

With this aim in view a large number of laboratory experimental investigations on shearing instruments were conducted by us. The investigations were made on compacted samples of loess soil of different degree of density. The optimal density of the investigated soils was found to be 17.3 kN/m^3.

From these investigations were obtained creep curves and isochronous curves for the compacted loess soils of different degree of compaction having the same moisture content ($\omega = 0.154$).

As a result of analysis of the isochronous curves a rheological equation of state, i.e. relationship among deformation stress and time is obtained in the form:

$$\tau = A(t)\lambda^{m(t)} . \qquad (1)$$

Here as creep function the coefficient of deformation A(t) – a quantity variable with time is employed (Vyalov 1978). From the results of the conducted investigations are determined values of the parameters A(t) and m(t) for different densities of loess soil.

Analysis of the results of these investigations show that the parameters A(t) and m(t) depend on degree of density, normal compacting pressure and change with time.

With increase in density of loess soil to the optimal one the parameter A(t) rises at all the values of normal compacting pressure and falls when density is above the optimal one. At the same degree of density of loess soil the parameter A(t) increases with rise in the normal compacting pressure while the parameter m(t) decreases . With increase in degree of density of loess soil the parameter m(t) decreases at all the values of the normal compacting pressure.

Moreover we find that both the parameters change with time: A(t) decreases with time, m(t), on the contrary, increases.

Table 1 shows degrees of changes in the parameters A(t) and m(t) with time in fractions of their initial values (at t=0; A(t)=A$_0$, m(t)=m$_0$) for different states of density of loess soil for three values of the normal compacting pressure.

Table 1. Degrees of change in parameters A(t) and m(t) with time in fractions of their initial values for different states of density of loess soil.

Density of the compacted loess soil in kN/m^3	Degree of change in the parameters A(t) and m(t) with time					
	σ=0.1 *MPa*		σ=0.2 *MPa*		σ=0.3 *MPa*	
	A(t)	*m(t)*	*A(t)*	*m(t)*	*A(t)*	*m(t)*
16.2	0.197	1.4	0.955	1.44	0.955	1.53
16.8	0.886	1.356	0.928	1.44	0.928	1.49
17.3	0.942	1.45	0.932	1.36	0.932	1.43
17.8	0.905	1.18	0.932	1.24	0.939	1.41

From the obtained creep curves were determined values of breaking stresses $\tau_1, \tau_2, \tau_3 ... \tau_i$ and time of failure $t_1, t_2, t_3,$ of the loess soil with moisture content $\omega = 0.154$ for its different states of density. On the basis of these data are plotted curves displaying relationship between breaking stress and time before failure (long-term strength curves) for loess soils of different density having the same moisture content. From the long-term strength curves are determined conditionally instantaneous strength τ_0, i.e. maximum strength characterizing resistance of the soil to rapid failure and limit of the long-term strength τ_∞ corresponding to the stress before exceeding which deformation is of attenuating nature and failure doesn't occur at any practically observed time of action of load.

Table 2 gives values of limit of the long-term strength in fractions of the conditionally instantaneous one for different states of density of the loess soil.

As seen from the data of Table 2 the strength of the loess soil at all the values of its density reduces with time approaching its long-term ultimate one for the given state of the soil. However, these reductions are different for different states of density of the loess soil. As the density goes up the extent of reduction in the strength of the loess soil with time decreases. For example, if the strength of the loess soil whose density $\rho_d = 16.2 kH/m^3$ decreases by 17-18% and amounts to 82-83 % of the conditionally instantaneous strength, i.e. $\tau_\infty = (0.82 - 0.83)\tau_0$, then at the optimal density of the loess soil equaling to $\rho_d = 17.3 kH/m^3$ the limit of its long-term strength is 88-90 % of the conditionally instantaneous strength, that is $\tau_\infty = (0.88 - 0.9)\tau_0$.

Table 2. Values of limit of long-term strength in fractions of conditionally instantaneous one for different states of density of loess soil.

Density of the loess soil in kN/m^3	Limit of the long-term strength in fractions of the conditionallyinstantaneous τ_∞ / τ_0 under normal pressures		
	$\sigma = 0,1 MPa$	$\sigma = 0,2 MPa$	$\sigma = 0,3 MPa$
16.2	0.83	0.8315	0.817
16.8	0.85	0.857	0.86
17.3	0.88	0.895	0.90
17.8	0.866	0.846	0.88

This regularity, however, is observed at an increase of the loess soil's density up to the optimal one. When the loess soil's density is above optimal (overcompacted samples of the loess soil of skeleton density $\rho_d = 17.8 kH/m^3$), the extent of reduction in the strengt5h with time increases and the limit of its long-term strength is 85-88% of the conditionally instantaneous one, i.e. $\tau_\infty = (0.88 - 0.9)\tau_0$. This statement agrees well with the statement that at higher values of the soil's density there takes place reduction in its resistance to external loads (Kharkhuta and Vasiliev 1975).

The reduction in strength and tendency to creep deformation of overcompacted loess soils are caused by excessive convergence of particles of the soils and their aggregates. At such convergence watercolloidal films in places of contact are removed and this leads to their compaction in other places. It results in the transition of a part of the bound water into the free one which facilitates relative movements of the particles and their aggregates.

A reduction of the loess soil's strength with time at different states of density is expressed by a logarithmic equation of the long-term strength in the form:

$$\tau(t) = \frac{\beta_\tau}{\ln \frac{t+1}{T_\tau}} \tag{2}$$

where $\tau(t)$ is shear resistance of the soil at a given moment of time; t- time (min.), parameters T_τ in minutes and β_τ in MPA determined experimentally.

Formula (2) is reduced to the linear form with its transformation into the following expression

$$\frac{1}{\tau(t)} = \frac{1}{\beta_\tau}\ln(t+1) - \frac{1}{\beta_\tau}\ln T_\tau$$

To check the applicability of the formula (2) the long -term strength curves obtained experimentally for different states of density of the soils having the same moisture $(\omega = 0.154)$ were transferred on a semi-logarithmic coordinate grid $\frac{1}{\tau(t)} - \ln(t+1)$. The straightening of the long-term strength curves on the logarithmic coordinate grid points to the applicability of the formula (2) for determination of the long-term strength of loess soils in their different states of density. From the results of processing of the experimental data values of the parameters β_τ and T_τ for different states of density of the loess soil were determined. The results of these determinations are presented in Table 3.

As seen from the data of Table 3, the values of β_τ and T_τ depend on the degree of density of the loess soil. With increase in density of the loess soil to the optimal one both these parameters rise at all the values of the normal compacting stress. When the loess soil's density exceeds the optimal value this regularity is violated, i.e. the values of these parameters are found to be less than at the optimal density.

Moreover we find that in all the states of density of the loess soil the value of the parameter β_τ goes up with increase in the value of compacting pressure.

Table 3. Values of parameters β_τ and $\ln T_\tau$ for different states of density of loess soil.

Density of the loess soil in kN/m^3	Parameters of equation of long-term strength	Under normal compacting pressures		
		σ=0,1 MPa	σ=0,2 MPa	σ=0,3 MPa
16.2	β_τ. MPa	10.125	11.6	12.676
	$\ln T_\tau$	-67.5	-60.824	-55.2
16.8	β_τ. MPa	11.364	14.925	18.02
	$\ln T_\tau$	-70.834	-70.20	-72.2
17.3	β_τ. MPa	14.493	25.64	26.434
	$\ln T_\tau$	-82.32	-106.6	-94.07
17.8	β_τ. MPa	13.814	15.385	23.337
	$\ln T_\tau$	-76.7	-59.31	-77.62

The results of solved numerical examples show that the limit of the long-term strength of compacted loess foundations of structures can be determined from the formula (2) with accuracy sufficient for engineering purposes.

CONCLUSIONS. From the results of the conducted investigations we conclude that at the optimal density of the loess soil under the same stresses the creep deformation in shear will be less. Owing to this phenomenon the least extent of reduction in strength with time is observed at the optimal density of the loess soil.

The obtained equations of creep and the long-term strength at the parameters known from the experiments allow to predict the performance of the compacted loess soil in the foundations of engineering structures with time.

REFERENCES

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